Bio. Res. Today 2025, 7(6):183-187

Biotica Research Today

e-ISSN: 2582-6654

June, 2025

Article ID: RT1808

Popular Article

Hydrogels in Modern Agricultural Practices: Significance and Applications

R. Preethadevi* **and R. Kiruthika**

Dept. of Agricultural Engineering, Nehru Institute of Technology, Coimbatore, Tamil Nadu (641 105), India

Open Access

Corresponding Author

R. Preethadevi

: nitdrpreethadevi@nehrucolleges.com

Conflict of interests: The author has declared that no conflict of interest exists.

How to cite this article?

Preethadevi, R., Kiruthika, R., 2025. Hydrogels in Modern Agricultural Practices: Significance and Applications. *Biotica Research Today* 7(6), 183-187.

Abstract

Population increase and climate change present modern agriculture major difficulties, including water scarcity, land degradation and rising food demand. Three-dimensional, hydrophilic polymer networks called hydrogels provide a hopeful solution by ensuring a progressive moisture release during droughts by absorbing and storing water up to 500-600 times their weight. Their special ability for regulated nitrogen release improves soil quality, lowers nutrient leaching and maximizes water utilization, hence solving inefficiencies in conventional irrigation. Synthetic as well as biopolymer-based hydrogels improve soil structure, increase porosity and encourage early seedling development. Made from natural elements like starch and chitosan, biopolymer hydrogels offer environmental safety and affordable sustainability as compared to conventional polymers. Modern precision agriculture methods combined with advanced hydrogel systems boost crop yield even in water-scarce areas. Hydrogel technology thus offers a significant economic and environmental benefit, making it absolutely innovative for sustainable agricultural practices.

Keywords: Biopolymer, Hydrogel, Sustainable agriculture, Water retention

Introduction

Modern agriculture is greatly challenged by water scarcity, soil deterioration and the growing demand for food production amid fast changing climatic conditions. With the agricultural sector using more than 70% of the world's freshwater resources, rising temperatures and severe weather events stress the available supplies, hence putting global water resources under notable strain (Ali *et al.*, 2024). These difficulties call for the implementation of creative and sustainable strategies that effectively use limited resources, given forecasts that the world population will near 10 billion by 2050. Often resulting in significant water losses *via* evaporation, runoff and ineffective nutrient delivery systems, traditional irrigation techniques finally reduce yields and raise manufacturing costs.

Figure 1: Hydrogel

Hydrogels (Figure 1) have developed as a possible answer to these urgent problems. Being three-dimensional, hydrophilic polymer networks, they have the extraordinary ability to absorb and hold great amounts of water, up to 500-600 times their own weight, therefore acting as efficient reservoirs. Hydrogels' remarkable capacity to hold water lets them slowly release moisture during drought, so guaranteeing that plants have a continuous water source when it is most urgently required (Narjary *et al.*, 2013). Apart from water retention, hydrogels are being used more and more as transporters for agrochemicals and nutrition. Optimizing

Article History

RECEIVED on 28th May 2025 RECEIVED in revised form 26th June 2025 ACCEPTED in final form 27th June 2025

plant development and nutrient absorption depends on their ability for regulated release, which can be fine-tuned by customized cross-linking densities and environmental stimuli such as pH, temperature and ionic strength (Azeem *et al.*, 2023; Tariq *et al.*, 2023).

Hydrogels' importance in agriculture is not only in their water retention capacity but also in their possible impact on soil management. Acting as soil conditioners, these substances can improve soil structure, boost porosity, lower compaction and help a more even distribution of nutrients and water over the root zone. Hydrogel use in dry and semi-arid areas can significantly increase crop survival rates, promote early seedling establishment and finally result in better agricultural yields and enhanced economic returns given water shortages. By guaranteeing the continuous release of fertilizers like urea over long periods, controlled-release formulations like nanocomposite hydrogel beads including mesoporous silica nanoparticles with chitosan have shown enormous potential. Such developments not only increase the efficiency of nutrient delivery but also reduce the dangers connected with over-fertilization and nutrient leaching, thereby helping the objectives of sustainable agriculture (Phan *et al.*, 2024).

Moreover, biopolymer-based hydrogels made from natural materials, including starch, chitosan, alginate, gelatin, lignin and guar gum; provide various benefits over their synthetic equivalents. Non-toxic, biodegradable and affordable, these natural hydrogels are ideal for extensive agricultural application where environmental safety and resource sustainability are top priorities (Tariq *et al.*, 2023). They not only offer environmentally suitable substitutes but also a calculated approach to using renewable natural resources, hence lowering reliance on petroleum-derived polymers perhaps left in the environment and causing long-term environmental damage.

Considering these advantages, this paper discusses the relevance of hydrogels in agriculture by means of their chemical and physical characteristics, processes of synthesis and mechanisms of action. It also addresses their several functions in increasing water retention, soil quality enhancement and regulated nutrient delivery facilitation, all of which are vital for overcoming the problems of water scarcity and raising crop output. This paper intends to give a thorough knowledge of how hydrogel technology can support sustainable agricultural practices in a water-limited world by combining recent research results from top studies and investigating creative uses, such as smart hydrogels that react to environmental cues, therefore benefiting researchers, legislators and industry practitioners.

Understanding Hydrogels: Composition and Mechanisms

1. Hydrogel Structure and Chemistry

Basically, hydrogels are three-dimensional, porous networks produced from cross-linked polymer chains. The mechanical stability and water absorption capacity of the hydrogel are determined by cross-linking, either chemical (covalent bonds) or physical (hydrogen bonding, ionic interactions, hydrophobic forces) (Tariq *et al.*, 2023). The physical state of a hydrogel could vary from a "glassy" (dehydrated) condition to a "rubbery" (hydrated) one, wherein it swells upon absorbing water. By means of hydrogen bonding, hydrophilic groups (*e.g.*, -OH, -COOH, $-NH_2$, $-SO_3H$) substantially influence binding water molecules, so imparting the material its high swelling index and water-retentive qualities (Phan *et al.*, 2024).

2. Types of Hydrogels

Hydrogels can be broadly classified based on different criteria (Table 1):

• *Natural (Biopolymer-based) Hydrogels*: Among these are items made from guar gum, lignin, gelatin, alginate, chitosan and starch. They provide benefits including biodegradability, biocompatibility and environmental friendliness (Tariq *et al.,* 2023).

• *Synthetic Hydrogels*: Composed of polymers including polyacrylamide, polyvinyl alcohol and acrylic acid derivatives, these hydrogels usually shine in durability and water retention but cause questions about environmental toxicity and biodegradability (Dimple *et al.*, 2024).

• *Hybrid Hydrogels*: These materials try to combine the advantages of high performance and sustainability by combining natural and synthetic polymers (Ali *et al.,* 2024).

3. Mechanisms of Water Absorption, Retention and *Release*

Osmotic forces and the existence of polar functional groups control the water absorption capacity of hydrogels. Water molecules are pulled into the polymer network when hydrogel is put into a wet environment, hence causing it to swell. Cross-linking density, ambient pH and temperature, among other things, affect the pace of swelling and the following water release. In agricultural uses, this regulated swelling and deswelling, often known as a "lag phase," "constant release," and "decay phase", allows hydrogels to preserve ideal moisture conditions and release encapsulated fertilizers and agrochemicals in a controlled way (Azeem *et al.*, 2023; Phan *et al.*, 2024).

Significance of Hydrogels in Agriculture

1. Enhancing Soil Water Retention

In agriculture, hydrogels play a major role in improving soil water retention. Hydrogels can keep moisture in the root zone with low rainfall by absorbing significant amounts of water and slowly releasing it. In arid areas, where every drop of water matters, this drop in irrigation frequency is particularly important. Research has demonstrated that hydrogels may greatly increase soil moisture level, thereby helping seed germination, plant establishment and general crop growth (Narjary *et al.*, 2013).

2. Improving Soil Structure and Nutrient Delivery

Apart from water retention, hydrogels are soil conditioners that improve soil structure by raising porosity and lowering compaction (Figure 2). Their capacity to gradually release nutrients and agrochemicals guarantees a more efficient nutrient absorption, minimizes nutrient leaching and lowers the environmental effect of too much fertilizer use. For example, nanocomposite hydrogel beads developed by

Table 1: Types of hydrogel

Hydrogel Type	Composition/ Materials	Synthesis/ Preparation Method	Key Properties	Agricultural Application	References
Starch-PAN hydrogel	Native cassava starch + polyacrylonitrile	Alkaline hydrolysis with macro-alkoxide initiated cross-linking.	Swelling capacity of ~682 g g^{-1} in distilled water.	Enhances water retention in soil; promotes early plant growth.	Tariq *et al.*, 2023
Starch-grafted hydrogel	Starch grafted with acrylic acid and 2-hydroxyethyl methacrylate	Graft polymerization (using N,N′-methylene bisacrylamide as cross-linker).	Swelling capacity ~95 g g^{-1} at pH 8.	Provides controlled release of agrochemicals for improved nutrient delivery.	Tariq *et al.*, 2023
MSNs/ Chitosan hydrogel beads	Mesoporous silica nanoparticles (MSNs) + chitosan	Ionic gelation/ chemical cross-linking (optimized for sustained release profile).	Sustained release of urea with high water retention.	Slow-release fertilizer delivery; improved long-term nutrient uptake.	Phan *et al.*, 2024
Dryland hydrogel	Generic superabsorbent polymer (synthetic/ biopolymer hybrid)	Field application techniques (formulations to reduce bulk density).	Enhances soil water-holding capacity and reduces soil compaction.	Boosts crop yield and resilience under arid or semi-arid conditions.	Dimple *et al.*, 2024
Smart/ Responsive hydrogels	Synthetic polymers (*e.g.*, PEG-based) often combined with biopolymers	Stimuli-responsive synthesis (tailored cross-linking density and environmental cues).	Responsiveness to pH/ temperature triggers controlled release.	Optimizes on-demand nutrient/ agrochemical delivery; enhances crop adaptability.	Ali *et al.*, 2024

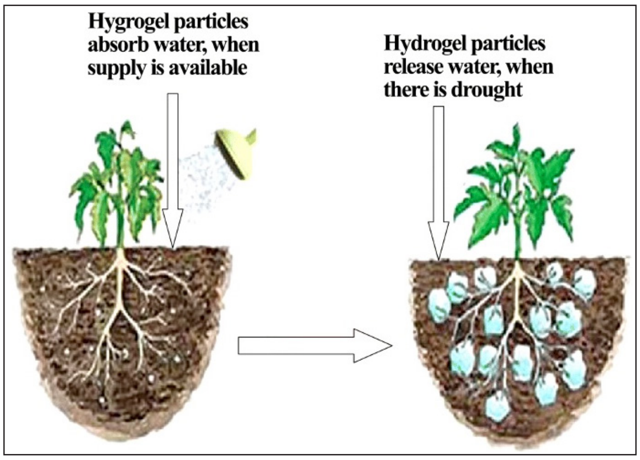

Figure 2: Change of soil porosity with the swelling of hydrogels

Phan *et al.* (2024) used mesoporous silica nanoparticles and chitosan to maintain urea release, hence maximizing the nutrient delivery in sandy soils.

3. Economic and Environmental Benefits

The integration of hydrogels provides environmental as well as financial benefits. Farmers can cut running expenses and manpower needs by cutting the demand for regular watering. Moreover, enhanced soil moisture and reduced nutrient leaching contribute to improved soil quality and augmented agricultural production. Biopolymer-based hydrogels are non-toxic, biodegradable and derived from renewable resources, so supporting sustainable agricultural practices and the United Nations Sustainable Development Goals from an environmental perspective (Ali *et al.*, 2024).

Applications of Hydrogels in Agricultural Practices

1. Soil Amendment and Conditioning

Hydrogels have been effectively utilized as additives in various soil types, especially in arid regions and sandy soils. These compounds stabilize the soil and improve its structure by increasing water retention and promoting better aeration. Better root development and nutrient dispersion are made possible by this decrease in soil compaction and increase in porosity. Research by Dimple *et al.* (2024), for instance, underlines the critical importance of hydrogels in dryland farming, where better water retention results in higher plant survival rates.

2. Controlled Release Technologies

The regulated release of fertilizers and agrochemicals is a creative use of hydrogels in agriculture. Encapsulated within the hydrogel matrix, nutrients are released slowly by means of diffusion controlled by environmental variables including pH and temperature. This regulated release not only maximizes plant nutrient absorption but also stops the quick drainage of soil nutrients. For example, nanocomposite hydrogel beads have shown consistent urea release over a long period, hence improving fertilizer use efficiency (Phan *et al.*, 2024).

3. Seed Coating and Germination Enhancement

Hydrogels can also act as seed coverings, shielding seeds from desiccation and giving them an instant source of water and nutrients following germination. Hydrogel coatings have been found to increase germination rates and encourage strong early growth by preserving a microenvironment ideal for seed germination. This use is especially pertinent for areas where variable rainfall or severe dryness may otherwise impede seedling establishment.

4. Innovations in Modern and Urban Farming

Hydrogels are vital growth media in modern urban and vertical agricultural systems when conventional soil is reduced. These systems run effectively with little water input because of their great water retention and nutrient encapsulation capabilities. Furthermore, developments like "film farming" methods and biodegradable hydrogel films show the commercial promise of hydrogel technology in controlled environment agriculture (Ali *et al.*, 2024).

Challenges and Limitations

1. Economic Considerations and Production Costs

Though they have many advantages, the high production expenses of hydrogels still limit their widespread use. Though their production methods are frequently costly and energy-intensive, synthetic hydrogels usually provide outstanding water retention. On the other hand, while more sustainable and environmentally friendly, biopolymer-based hydrogels could show weaker mechanical strengths or need more regular replacement because of quicker biodegradation (Tariq *et al.*, 2023). When thinking about scalability for smallholder farmers in underdeveloped areas, these financial elements are quite important.

2. Environmental Impact and Sustainability

Though biopolymeric hydrogels are non-toxic and biodegradable, questions are still exist about the long-term consequences of synthetic hydrogels. Possible problems include negative consequences on soil microbiology and non-degradable residue deposition in soil. Promoting sustainable farming operations depends on balancing the excellent performance of synthetic hydrogels with the environmental advantages of biopolymer-based alternatives. Regulations and policies are required to guarantee that the usage of synthetic hydrogels does not add to long-term environmental deterioration (Ali *et al.*, 2024).

3. Performance Variability

Many elements, including soil type, climate conditions and particular crop needs, will determine how well hydrogels function in agriculture. Variations in cross-linking density or the presence of rivaling ions in the soil could cause inconsistencies in swelling behavior or nutrient release rates. Such variation highlights the importance of site-specific hydrogel dose and formulation calibration to guarantee uniform effectiveness in various agricultural settings (Dimple *et al.*, 2024).

Future Prospects and Research Directions

1. Advances in Material Science

Future studies in hydrogel technology are anticipated to center on the creation of "smart" hydrogels reacting to environmental factors including pH, temperature, light and ionic strength. By means of precise tuning of the release of nutrients and agrochemicals, these stimuli-responsive systems can maximize crop performance under different circumstances. Improvements in the synthesis of hybrid hydrogels combining natural and synthetic polymers could offer the two benefits of high water retention and biodegradability (Tariq *et al.*, 2023).

2. Integration with Modern Farming Technologies

Future research seems to be in the direction of hydrogels combined with precision agriculture technology. Farmers may maximize water utilization and nutrient delivery on a real-time basis by combining hydrogels with moisture sensors, automated irrigation systems and data-driven management platforms. Particularly in urban and vertical farming uses, such methods not only improve crop output and quality but also help to conserve resources greatly (Ali *et al.*, 2024).

3. Policy, Regulation and Commercialization

Supportive regulatory systems and market incentives are very vital if hydrogels are to be widely used in agriculture. Clear rules on the safe manufacture, use and disposal of hydrogel products have to be set by policymakers. Especially for small-scale farmers, financial incentives, subsidies, or cost-sharing initiatives could help to balance first expenses and promote uptake. Scaling up production and guaranteeing product quality will depend on commercial alliances among research institutions, industry and government agencies (Dimple *et al.*, 2024).

4. Research Gaps and Areas for Future Study

There is a pressing need for extensive long-term field studies that assess the performance, environmental impact and economic viability of hydrogel applications in diverse agricultural settings. Future research should address the following areas:

i) The optimization of hydrogel formulations for specific soil types and crops.

ii) Life cycle assessments to evaluate the environmental footprint.

iii) The interactions between hydrogels and soil microbiota over extended periods.

iv) Strategies for the cost-effective production of biodegradable hydrogels.

Conclusion

Modern agriculture depends on hydrogels since they address important issues related to soil degradation and water scarcity. Their extraordinary water-holding capacity, which may absorb up to 500-600 times their weight in water, together with their prospective function as controlled-release transporters for nutrients and agrochemicals, makes them especially useful in dry and semi-arid areas (Narjary *et al.*, 2013). Especially crucial for ensuring environmental safety and resource preservation are biopolymer-based hydrogels, such those produced from starch and chitosan, which have additional advantages in terms of biodegradability, non-toxicity and sustainability (Tariq *et al.*, 2023).

From improving soil water retention and conditioning to allowing exact fertilizer distribution *via* smart, stimuli-responsive devices, hydrogels have several applications. Such developments have the potential to change irrigation methods and help to produce crops sustainably. But, ongoing study, legislative assistance and technology integration will help to resolve issues about manufacturing costs, environmental effects of synthetic versions and performance variation.

By increasing water-use efficiency, strengthening soil quality and enabling regulated fertilizer delivery, hydrogels, in conclusion, offer a hopeful path toward sustainable agriculture methods. Their capacity to change conventional farming methods, especially in water-stressed areas, is important. Future developments in hydrogel science, together with efficient rules and market incentives, could make these materials a foundation of contemporary, sustainable agriculture. To improve formulations, maximize application methods and completely fulfill the potential of hydrogels in addressing world agricultural issues, more cross-disciplinary cooperation is absolutely required.

References

Ali, K., Asad, Z., Agbna, G.H.D., Saud, A., Khan, A., Zaidi, S.J., 2024. Progress and innovations in hydrogels for sustainable agriculture. *Agronomy* 14(12), 2815. DOI: https://doi.org/10.3390/agronomy14122815.

Azeem, M.K., Islam, A., Khan, R.U., Rasool, A., Qureshi, M.A.R., Rizwan, M., Sher, F., Rasheed, T., 2023. Eco-friendly three-dimensional hydrogels for sustainable agricultural applications: Current and future scenarios. *Polymers for Advanced Technologies* 34(9), 3046-3062. DOI: https://doi.org/10.1002/pat.6122.

Dimple, K.T., Paul, A., Kakoti, M., Shridhar, A.K., Shobnur, S., Robertson, A., Alam, S., 2024. Hydrogel in drylands: A review. *International Journal of Environment and Climate Change* 14(8), 416-422. DOI: https://doi.org/10.9734/ijecc/2024/v14i84362.

Narjary, B., Aggarwal, P., Kumar, S., Meena, M.D., 2013. Significance of hydrogel and its application in agriculture. *Indian Farming* 62(10), 15-17.

Phan, M.C., Tran, H.T.H., Ha, N.N., Phan, V.H.G., Nguyen, V.Q., 2024. Fabrication of Hydrogel beads based on mesoporous silica nanoparticles/chitosan and application as a slow-release fertilizer. *Journal of Technical Education Science* 19(SI05), 55-66. DOI: https://doi.org/10.54644/jte.2024.1578.

Tariq, Z., Iqbal, D.N., Rizwan, M., Ahmad, M., Faheem, M., Ahmed, M., 2023. Significance of biopolymer-based hydrogels and their applications in agriculture: A review in perspective of synthesis and their degree of swelling for water holding. *RSC Advances* 13, 24731-24754. DOI: https://doi.org/10.1039/d3ra03472k.